Superconductivity Induced Electronic Excitation and Phonon Anomalies in Trilayer $Bi_2Sr_2Ca_2Cu_3O_{10}$

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Charge and lattice dynamics along the c axis perpendicular to the CuO_2 superconducting (SC) planes were studied in a Bi2223 crystal with infrared ellipsometry. The far-infrared (FIR) conductivity data reveal that a strong absorption band corresponding to a transverse Josephson plasmon develops as the crystal enters the SC state. The effect of the FIR spectral weight increase opposes the spectral weight decrease in conventional SC's. This unusual effect highlights that an anomalously large energy scale beyond the FIR range can be attributed to SC condensate formation in high-T_c superconductors. We also observe phonon anomalies, suggesting that the Josephson currents lead to a drastic variation of the local electric field within the closely spaced CuO_2 planes.

The transition from a normal metal to a superconductor (SC) below the critical temperature, T_c, is accompanied by a redistribution of spectral weight (*SW*) for the real part of the complex optical conductivity, $\sigma(\omega)$, from finite frequencies in the normal state (NS) into a δ-function at zero frequency in the SC state. For classical SC's, the energy gap determines the frequency range over which the *SW* of the δ-function is collected. That noticeable change occurs only for $\omega < 6\Delta$ (Ferrell-Glover-Tinkham (FGT) sum rule). Recently, it was found that the FGT sum rule is partially violated for the c axis response of some high-T_c cuprate compounds: The *SW* loss in the FIR below T_c is smaller than the *SW* of the δ-function at zero frequency. It implies that SC pairing involves a very large frequency scale and may rule out conventional mechanisms that rely on low-frequency bosons, such as phonons. Instead, it supports models where a decrease in the c axis kinetic energy below T_c provides a significant contribution to the SC condensation energy.

These far-reaching implications call for further experiments on a compound with a larger, more easily identified *SW* transfer. The best candidates are multilayer high-T_c compounds, which contain more than two CuO_2 planes per unit cell. Here we present ellipsometric data of the c axis dielectric response of the trilayer compound $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi2223). The ellipsometric measurements have been performed at the infrared beamlines of the synchrotrons at ANKA in Karlsruhe, Germany and at NSLS. The brilliance of the synchrotrons enables us to obtain accurate data in the FIR spectral range, even on mm-sized samples.

Figure 1 shows the real part σ_1 of the c axis optical conductivity of Bi2223 at the three doping levels. The most prominent feature is the broad absorption band around 500 cm^{-1}, which appears below T_c and grows rapidly with decreasing temperature. The center of this band shifts towards higher frequencies with increasing doping. A similar band was previously identified in the bilayer compounds $YBa_2Cu_3O_{7-\delta}$ and $Bi_2Sr_2CaCu_2O_8$ where it has been attributed to a transverse Joseph-

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son-plasma resonance (t-JPR). The *SW* of this feature in Bi2223 is very large and causes a considerable increase in the FIR-*SW* below T_c. This apparent increase in the *SW* is certainly not expected for any conventional SC where the FIR-*SW* should be removed and transferred to the δ-function at zero frequency (**Figure 2a**). **Figure 2b** shows the SC induced change of the FIR conductivity in Bi2223. The data represent a striking manifestation of the violation of the FGT sum rule. They highlight that a significant amount of *SW* is transferred from higher frequencies to the absorption band near 500 cm⁻¹. We emphasize that within the Josephson superlattice model (JSM) the *SW* of the t-JPR belongs to the SC condensate as much as the one of the δ-function at zero frequency.

Figure 1 shows that the t-JPR formation is also associated with an anomalous temperature dependence of the phonon modes. Particularly interesting are the contrasting *T* dependences of the modes at 360 and 400 cm⁻¹. As shown in **Figure 3a**, the mode at 360 cm⁻¹ loses a significant amount of its SW below T_c, while the latter one gains in the *SW*. Both phonons are oxygen bond-bending modes with the eigenvector diagrams in **Figure 3b**. Their contrasting behavior is explained by the JSM. **Figure 3c** shows the charge dynamics corresponding to the t-JPR, where $\kappa(\omega)$ denotes the charge density that alternates from one outer plane to the other. The onset of the Josephson currents j_1 and j_2 between the CuO₂ layers below T_c can lead to a significant change of the dynamical local electric field inside the trilayer, E_1, inside the spacing layer that separates the trilayers, E_2, and at the outer CuO₂ layers, E_3. The strength of a given phonon mode is determined by the local field at the participating ions participating and by the mode polarizability. The main difference between the oxygen bond-bending modes is in the relative phase and amplitude of the inner and outer-plane oxygen vibrations: The mode at 360 cm⁻¹ consists predominantly in the oxygens' vibration in the outer CuO₂ planes (O1), and the latter one involves vibrations in the middle CuO₂ (O4) plane. Following this model, we estimate that the average magnitude of E_3 at O1 ion sites is strongly suppressed below T_c, while the magnitude of E_1 inside the trilayer at O4 sites increases. The local field effect leads to the observed behavior of the oxygen bond-bending modes in the SC state. These phonon anomalies clearly reflect a transition from a confined state (incoherent intra-trilayer conductivity) to a state where the CuO₂ planes are Josephson-coupled. They demonstrate that, in the SC state, the local electric field can exhibit enormous unit cell variations.
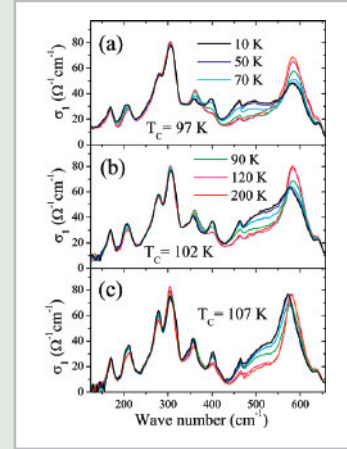

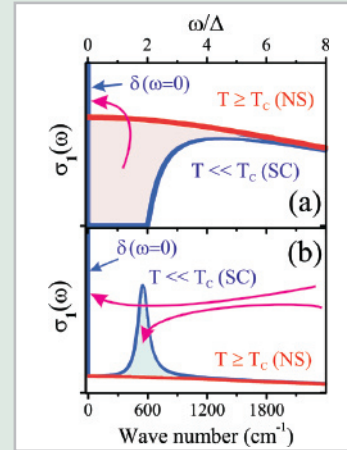Figure 1. Real part, $\sigma_1(\omega)$, of the FIR c axis conductivity of Bi2223.

Figure 2. (a) Sketch of the SC induced change of the FIR conductivity (a) for classical materials with a s-wave SC order parameter. (b) as observed in Bi2223.
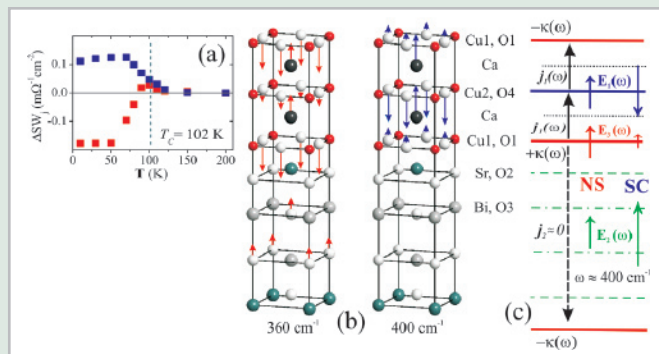

Figure 3. (a) Relative SW changes of the phonons at 360 cm⁻¹ (red squares) and 400 cm⁻¹ (blue squares) with decreasing temperature. (b) Calculated oxygen bond-bending A₂ᵤ eigenmodes of Bi2223. (c) Schematic representation of the charge density fluctuations associated with the IR active plasma mode and the related local electrical field in the normal and SC states in the frequency range of the bond-bending modes.